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Quantum Optics with Quantum Dots in Photonic Nanowires

J.M. Gérard^{1*}, J. Claudon¹, J. Bleuse¹, M. Munsch¹, N. Gregersen² and P. Lalanne³

¹CEA-CNRS joint group 'NanoPhysique et SemiConducteurs', CEA, INAC, SP2M, 38054 Grenoble, France

²DTU Fotonik, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark

³Laboratoire Charles Fabry de l'Institut d'Optique 91127 Palaiseau, France

Abstract : We review recent experimental and theoretical results, which highlight the strong interest of the photonic wire geometry for solid-state quantum optics and quantum optoelectronic devices.

OCIS codes : (270.5580), (350.4238), (250.5590)

1. Introduction

Over the last 20 years, major efforts have been devoted to the tailoring of the optical properties of semiconductor emitters using optical microcavities and photonic crystals. Photonic wires, initially introduced in the context of microlasers [1], have recently been used by our group to control the spontaneous emission of self-assembled InAs quantum dots (QDs) and to build highly efficient single-mode single photon sources. We use in these experiments cylindrical GaAs photonic nanowires, defined using a top-down approach based on electron-beam lithography and reactive-ion etching (see fig.1).

2. QD spontaneous emission control in photonic wires

For an optimum diameter $d/\lambda \sim 0.2$, such structures provide a strong lateral confinement of the guided mode, while the amplitude of non-guided modes is drastically damped within the wire due to a dielectric screening effect [2]. As a result, theoretical calculations show that the fraction of the spontaneous emission (SE) that is coupled to the guided mode HE_{11} reaches $\beta=95\%$ for an emitter on-axis, provided the polarization of its dipole is orthogonal to the wire axis [3]. Unlike optical microcavities, which exploit the *SE enhancement* into the cavity mode (Purcell effect), photonic wires thus rely on the *inhibition* of the SE into “useless” modes for providing this “nearly” single-mode behavior of the SE.

The study of QDs embedded in photonic wires by time-resolved PL highlights this crucial inhibition effect at work. Very long lifetimes (up to $\times 17$ v.s. QDs in bulk GaAs) are observed for those QDs that are weakly coupled to the guided mode [2]. This is the case for QDs located close to the wire edge, or for QDs in very narrow wires ($d/\lambda < 0.15$), for which the guided mode is mostly located outside the wire.

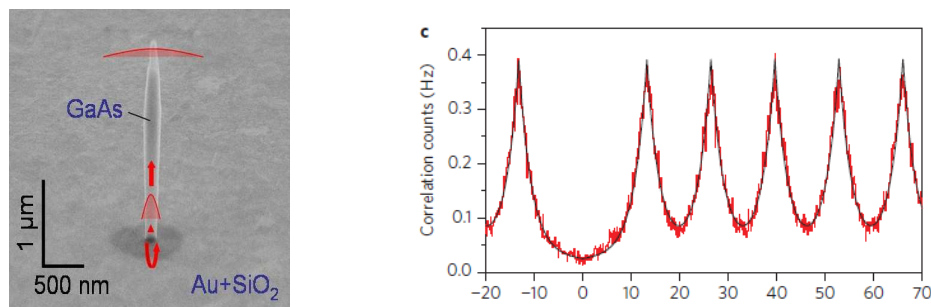


Figure 1: (left) View by scanning electron microscopy of a tapered GaAs photonic wire on top of an hybrid Au/SiO₂ mirror. (right) Photon correlation histogram obtained for the exciton line of a QD in a photonic wire at saturation, under pulsed optical excitation. The fit to theory reveals the absence of multi-photon pulses ($g^{(2)}(0) < 0.008$). From [7].

Photonic wires with an axial symmetry support two polarization-degenerate guided modes. In view of applications, it is often desirable to control also the polarization of the spontaneous emission of embedded emitters. In micropillar resonators, a breaking of the axial symmetry can be used to lift the degeneracy of the fundamental cavity mode, and couple the emitter to a single and polarized cavity mode [4]. In a similar spirit, we have studied photonic nanowires with an elliptical cross-section. For dimensions of the ellipse around λ/n (long axis) and $\lambda/2n$ (short axis), the two guided modes exhibit drastically different behaviours. The first mode, with a linear polarization

oriented along the ellipse major axis, is tightly confined inside the wire, while the second mode is mostly located outside the photonic wire. As a result, one expects unpolarized semiconductor emitters (such as quantum well or quantum dot excitons) to display a truly single-mode, linearly polarized spontaneous emission, when embedded in such photonic wires. Furthermore, this single mode behaviour is maintained over a broad wavelength range, since no resonant effect enters into play. Experiments on elliptical GaAs photonic wires with embedded InAs quantum dots fully confirms these predictions [4]. In particular, the fraction of collected photons with the desired linear polarization reaches as much as 95 % for the best QDs, located close to the wire axis.

3. Application to single mode single-photon sources

A highly efficient single photon source (SPS) based on a QD in a photonic wire has recently been developed [3]. In order to ensure a good collection of the single photons, the far field radiation diagram of the wire is carefully tailored using a broadband SiO₂-Au modal mirror at the bottom side [5] and a smooth tapering of the wire tip [6]. Combining these building blocks, one predicts a record high SPS efficiency (>90%) over a 70 nm-broad spectral range for standard collection optics (NA~0.75) [2]. The optical characterization performed using microPL and photon correlation experiments fully confirm the theoretical predictions: a record high efficiency (72%) is obtained [7], to be compared to 40% at most for the best published results for SPS based on cavity effects. Furthermore, a very pure single photon emission ($g^{(2)}(0) < 0.01$) is observed for all pumping powers, up to the saturation of the emission of the QD exciton [7]. This is a crucial asset vs cavity-based QD-SPS, whose $g^{(2)}(0)$ is plagued by “cavity feeding” [8] effects under strong excitation conditions [9,10].

Quite remarkably, these photonic wires, with their integrated mirrors and tapered tips, provide a broadband control of the SE of embedded emitters. They thus offer appealing novel opportunities for the development of SPS based on spectrally broad emitters (such as F centers in diamond), wavelength tunable sources or efficient sources of entangled photon pairs. Finally, novel designs based on inverted tapers will also enable the efficient operation of these quantum optoelectronic devices under electrical pumping [11].

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* jean-michel.gerard@cea.fr